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ENGINEERING EXPERIMENT STATION
LAFAYETTE, INDIANA

EXPERIMENTAL INVESTIGATION OF HIGH HEAT-RELEASE COMBUSTION CHAMBERS

ARMY AIR FORCES COOPERATIVE RESEARCH PROJECT
M-125
Contract No. W535-ac-38886

PURDUE UNIVERSITY
OFFICE OF THE DEAN OF ENGINEERING
LAFAYETTE, INDIANA

May 10, 1945

Commanding Officer
Army Air Forces
Air Technical Service Command
Wright Field
Dayton, Ohio

Subject: Cooperative Research Project M-125,
Contract No. W535 ac-38886, Item No. 2.

Gentlemen:

I am attaching herewith three copies each of two reports completing Item 2 of contract W535 ac-38886. These reports are "Investigation of Jet Propulsion Devices", by N. Kulik and "Experimental Investigation of High Heat-Release Combustion Chambers", by O. C. Cromer and J. E. Yingst.

The first of these reports reviews the results of our investigation of jet propulsive devices from both a theoretical and experimental standpoint. The theoretical study has been made to investigate the influence of various factors on the efficiency of jet propulsion systems and also a theoretical and experimental study of factors that might lead to improvement in the application of these systems. In the investigation of the possible methods of improvements, experimental and theoretical studies have been made on the possibilities of thrust augmentors. The results of our studies, have shown that under certain conditions it is possible to increase the thrust of a jet engine by about 50%. This advantage is obtained only at low velocities and would be of value under take-off conditions.

The second report in completing this item is concerned with the experimental investigation of high heat-release combustion chambers. This part of the investigation is a continuation of a previous report furnished you on this same subject. It was found that heat-release as high as 20,000,000 Btu/hr per cu ft of corrected burner volume could be obtained. The temperatures in the burner to obtain such high heat-releases were in excess of 2800°F which caused material problems. Some experimental work was done in earlier designs to determine the effect of cooling of burner walls by making a burner with coil of 1/4" steel tubing through which cooling water was circulated. It was found that the combustion process was extremely critical to the burner wall temperature. Any slight reduction in the temperature of the burner wall resulted in incomplete combustion within the burner chamber. Subsequent designes attempted to control wall temperature by combustion air circulation.

Respectfully submitted,

A. A. Potter

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EXPERIMENTAL INVESTIGATION OF HIGH HEAT-RELEASE COMBUSTION CHAMBERS

by

D. C. Cromer

J. K. Yingst

Army Air Forces Cooperative Research Project

M-125-2

Contract No. #535 ac-38806

I. SUMMARY

This investigation was concerned with the design of a high rate heat-release combustion chamber which would operate consistently, dependably, and efficiently, the greatest emphasis being placed on the first two of these operating characteristics.

The release of great quantities of heat in a small volume and with low pressure drop in the burner presents a number of difficult problems. This investigation has been concerned with a fundamental study of the factors which influence the design and performance of such a combustion chamber. This has resulted in many experiments with different designs, and facts learned through these experiments have been used to progressively refine the designs.

Previous work on the subject had shown that heat-release rates as high as 20,000,000 B/hr per cubic ft of corrected burner volume could be obtained, i.e., that it was possible to so control the mixing of fuel and air, the ignition of the mixture and the burning of the mixture that the great heat-release rate given above could be reached. Such heat-release rates were maintained for only a short period at the beginning of this work, however. The high heat-release rates were accompanied by rapid deterioration of the burner by the high temperatures reached in the combustion process. Temperatures in excess of 2800° F were developed in all of the chambers tested. Obviously, the question of materials to withstand such temperatures was a difficult one. This problem was the limiting factor in all work done. All

designs arrived at were influenced more by the necessity of withstanding the extreme temperatures within the burner than by any other consideration, for very little could be done to improve starting operation, efficiency, etc., until a chamber having a burner with an appreciable life was perfected.

Since it was impossible to secure burner materials which would withstand the excessive temperatures of the combustion process, a different approach to the problem was used. Combustion chambers were designed with the idea of cooling the walls of the burner to a safe operating temperature. In an early design, the portion of the burner where the greatest combustion occurred was a coil of 1/4" steel tubing through which cooling water was circulated. The flow of water could be regulated so as to maintain different burner temperatures. Although this burner was found impractical, one important point was observed: the combustion process was extremely critical to the burner wall temperature.

The idea of cooling the burner by circulating a liquid coolant was abandoned. Instead, the large quantities of air used in combustion were utilized for cooling purposes. A number of chambers were designed so that the flow of air was used to cool the burner. Some of these designs were failures, others were satisfactory. In general, however, the utilizing of the combustion air for cooling the burner showed great promise. Many previously unknown facts were learned and a number of old problems were solved by the new approach.

The problems encountered and the measures taken to solve them are discussed in detail under Combustion Chamber Studies. It should be emphasized that the solutions to those problems now seem simple and easily understood; however, at the time they were encountered they were of major importance because of the lack of knowlege as to their improtance in the overall development of the combustion chamber.

A combustion chamber has been designed and built incorporating all the knowledge and experience gained through observations on and experience with previous chambers. Its operation has confirmed the validity of certain ideas regarding the design of the chamber.

II. OBJECT

The object of this investigation was to develop fundamental information on the design of high heat-release rate combustion chambers. The ideal combustion chamber was to be suitable for application to jet propulsion power units or gas turbines or combinations of both. The combustion chamber was to be small in size, consistent in operation, and was to be capable of liberating several million Btu per hour per cubic foot of combustion chamber volume. Furthermore, a combustion chamber of simple design having an appreciable life was desired.

This investigation was carried on with these basic requirements in mind. Although the combustion chamber was to be suitable for application with jet propulsion devices and also gas turbines, no attempt was made to study or investigate either jet propulsion units or gas turbines other than to get information concerning the combustion chambers of such units. This investigation was concerned with the study of the effect of design on a high heat-release rate combustion chamber and the collection of fundamental information on their performance.

III. APPARATUS

Figure 11 in the Appendix is a diagram of the arrangement of the apparatus used in the investigation of the high heat-release rate combustion chambers. Basically the apparatus consisted of two flow circuits: one for the fuel and one for the air. No. 3 grade fuel oil having an A.P.I. value of 38 was used as the fuel. It was felt that representative results could be obtained with such a fuel since its heating value compared favorably with that of other typical fuels such as kerosene or low grade gasoline. In addition, the No. 3 grade oil was better suited from the safety standpoint, and facilities for handling that grade fuel were already available in the laboratory.

When the investigation was first started, the idea of using a gear pump for delivery of the fuel oil under pressure to the fuel nozzle seemed worthwhile. Later, however, the method shown in Fig. 11 was adopted. This fuel system consisted of a fuel supply tank, a pressure supply tank, a fuel-rate gage, and such control valves and gages as were necessary. The fuel supply tank was a cylindrical, steel tank capable of withstanding pressures of 2000 psi or more; it had a capacity of about 18 gallons. The pressure was supplied by nitrogen in commercial nitrogen bottles which were connected directly to the apparatus. Valves were installed so that any given pressure (up to the safety limit of the fittings) could to maintained.

The rate of fuel consumption was measured by a rotameter placed in the fuel line just ahead of the fuel flow control valve. This rotameter read directly in pounds per hr and had been calibrated especially for the fuel used by the manufacturer. The rate of flow was controlled by the fuel flow control vavle and the pressure of the fuel at the nozzle could be read. Several different capacity fuel nozzles wereused and nozzles with different spray angles were tested to find the one having the best characteristics.

The air supply was composed of two systems - a primary air supply and a secondary air supply. The reasons behind the two separate air supplies are given in detail in Combustion Chamber Studies. At first one air supply was sufficient. This was later called the primary air supply. This air supply was composed of a compressor driven by an A.C. motor, a storage tank with a relief valve, a control valve for regulating the flow of air to the combustion chamber, and a pressure gage. The primary air was introduced at the bottom of the chamber just ahead of the fuel-air cone. The compressor was a four cylinder, single-stage compressor capable of delivering air at 135 psia pressure. The volume of air supplied was measured by a displacement type meter placed at the inlet to the compressor. This single air supply was used in the investigation of the first four chamber designs.

It later became necessary to add an additional air supply to the set-up. This was the secondary or low pressure air supply. The secondary air supply contained a compressor driven by a D.C. motor, control valves for regulating the amount and distribution of the air, a relief valve for adjusting the pressure head on the compressor, and a pressure gage. The compressor was a Roots type. The volume of air flowing was measured by an orifice meter placed on the inlet to the compressor.

The combustion chambers were tested in a vertical position. They were all mounted on scales so that the amount of thrust could be measured. The thrust measurements were discontinued, however, because no effective way of isolating the combustion chamber from the effects of the air leads was found. The exhaust gases from the combustion chambers were expelled into an exhaust hood connected to a stack.

Because of limitations of space the ignition system is not shown in Fig. 11. The fuel-air mixture was ignited by a spark from a spark plug. The spark was supplied by a spark coil and batteries. Although a number of difficulties were encountered in the ignition of the charges, the same apparatus was used with all of the combustion chambers.

IV. INTRODUCTION

Previous work had shown that it was possible to release great quantities of heat in a small combustion volume. In fact, heat releases as high as 20,000,000 B/hr per cubic foot of corrected combustion chamber volume had been obtained. Such heat-release rates were maintained for only brief periods, however.

The ultimate goal of extending the period of high heat-release rate to an appreciable or useful length of time presented a number of perplexing, difficult problems. Furthermore, most of these problems were interrelated to such an extent that the solution of one seriously and adversely affected the others. As a result, the investigation of high heat-release rate combustion chambers became a task of considering in turn the effect of a number of known variables on the overall performance of the chamber, designing chambers accordingly, and then testing them.

It should be obvious that such a procedure was lengthy and involved. However, this procedure was valuable in that a number of interesting and important facts became known that might otherwise have remained obscure except for this trial and error method.

The problem of releasing great quantities of heat is not in itself a great problem, but the problem of great heat-release rates in a small volume and with certain limitations as to proportions of the combustion chamber, velocities throughout the chamber, pressures within the chamber, efficiency of combustion, consistency of operation, control of temperatures throughout the chamber, durability of the chamber under operating conditions, materials available and suitable for the chamber, ease with which combustion can be started in the chamber, and suitable ignition methods became exceedingly complex.

Some of the limitations just mentioned were not obvious at the beginning of this investigation; in attempting to meet certain of the limitations, others came into being. That is, it soon became evident that in some cases it was impossible to fulfill certain requirements without infringing on certain other ones. Thus, additional limitations were imposed on those already existing.

For example, the efficiency of combustion was influenced by the velocities of the gases through the chamber; the velocities of the gases influenced the temperatures within the chamber, and the temperatures within the chamber influenced the efficiency of the combustion as well as a number of other things. Now, if the velocity of the gases through the chamber were changed to improve the combustion efficiency, this change would cause changes in temperatures within the chamber which would in turn affect the combustion efficiency, perhaps adversely. Thus, one change caused an unanticipated change which induced still another change.

It shouldn't be difficult to appreciate the problems imposed by such a high degree of dependency of the variables in an investigation such as this. As a result of this dependency, progress in developing a suitable chamber was slow and tedious. It necessitated a program of constructing a chamber, testing it, analyzing its performance. In some cases these changes were beneficial; in others, they were either neutral or even detrimental to performance.

A great amount of information was gathered on the problem of the high heat-release rate combustion chamber. This information is in a rather intangible form, however, i.e., it cannot be put down as data in table form. As yet, it has been impossible to test a chamber to such an extent that performance characteristics can be recorded for study and analysis. In the process of testing chamber designs, certain facts have become known, usually by observation, and these facts have influenced the design of the next chamber. Thus, the knowledge on the subject is not revealed by tables of data or series of performance curves, but rather by progressive refinements in combustion chamber designs.

V. COMBUSTION CHAMBER STUDIES

It was shown in an earlier report on this project th the very high heat release rate is accomplished at the expense of combustion chamber life, i.e., the combustion chamber, particularly the burner, deteriorates rapidly because of the high temperatures accompanying the high heat-release rate. The report further showed that combustion-chamber life could be prolonged by decreasing the heat-release rate. Thus, a choice existed between high heat-release rates with short burner life or low heat-release rates with long burner life.

Neither of these two extremes is entirely desirable nor does either one represent any particular accomplishment. The real problem is that of obtaining high heat-release rates and also long burner life. Therefore, the object of this investigation has been to develop a combustion chamber which will liberate heat at rates exceeding 20,000,000 B/hr per cubic foot of corrected combustion chamber volume, which will operate consistently and efficiently, and which will have an appreciable life.

Before going further, a description of the general arrangement of the combustion chamber should be given. The combustion chamber assembly was made up of a burner unit, a fuel nozzle and air cone unit, an exhaust nozzle, an air inlet and the combustion chamber walls embracing the entire assembly. The combustion chamber was placed in a vertical position for convenience.

The burner unit where combustion actually took place was a cylindrical chamber separated from the combustion chamber walls by an annular air space. At the bottom of the combustion chamber was the air inlet allowing the air to enter vertically and centrally. In the path of the air stream was an air cone containing the fuel nozzle and perforated with air holes to allow air to enter around the nozzle and mix with the fuel. The nozzle was in the apex of the cone and sprayed the fuel in the direction of air flow; the apex of the cone pointed opposite the direction of air flow. A spark plug was placed so that a spark occurred in the air cone and ignited the rich mixture.

The burning rich mixture was discharged from the air cone into the burner. The lower portion of the burner contained a mixing chamber; this mixing chamber contained air holes or spaces which allowed more air to mix with the rich mixture to produce a highly combustible mixture. Burning then occurred in the upper portion of the burner and the hot gases were discharged through the exhaust nozzle.

This arrangement of the combustion chamber was used throughout the entire investigation except for certain changes which will be mentioned later in this report. Figure 4 shows the combustion chamber assembly just described.

The design of the burner was the source of greatest trouble. The two problems causing difficulty were proper mixing of fuel and air and resistance of the bur er to the intense heat of the combustion process. The operation of the chamber was extremely critical to the fuel-air ratio of the mixture and to the position within the burner where proper mixing was achieved. These facts were of great influence in the design of the burners. A number of different burners were designed and tested. The same combustion chamber assembly shown in Fig. 4 was used except for the burner.

The question of finding materials for the burner was the primary problem in the design of the combustion chamber. Tem eratures in excess of 2800 ^{o} F were developed in all the chambers designed, constructed, and tested. Obviously, the selection of materials to withstand such temperatures was a difficult one. A number of ideas relative to materials were either tested in actual practice or investigated through literature and actual correspondence with manufacturers.

The idea of ceramic materials for the burner itself seemed worthy of experimental study, so a burner unit was constructed along this line. This burner unit, burner No. 1, is shown in Fig. 1. The portion of the burner where the greatest combustion occurred was a porcelain cylinder 2-3/4" x 7" with 3/16" walls. The lower portion of the burner was a mixing chamber. This contained a number of air holes and served to produce a combustible mixture from the rich mixture proceeding from the region of the fuel nozzle and air cone

A number of such burners were tested, and the results were very bad. In each case, the porcelain section was broken and fractured into many segments. The manufacturer had specified an upper temperature limit of 3000°F for this porcelain and there was no reason to believe that this limit had been approached within 300°F. Other causes for failure may havd been shocks due to vibrations within the burner or stresses within the walls caused by a difference in temperature between the interior and the exterior surfaces of the burner.

This burner was abandoned in favor of a design along different lines. Since it was impossible to secure a heat resistant material, the problem was approached from the standpoint of cooling the walls of the burner to a safe operating temperature.

In the first attempt to cool the burner, a water cooled section was employed. This water cooled section was the portion of the burner where the greatest heat release occurred as determined from previous experiments. This burner, burner No. 2, is shown in Fig. 2. The lower section was a mixing chamber; air entered through the air holes and produced a highly combustible mixture from the rich mixture issuing from the air cone. The center section of the burner was the combustion space and was the water cooled section. This section was a coil made of 1/4" chromium-plated, steel tubing. The upper section was a plain steel cylinder conducting the exhaust gases to the exhaust nozzle. These formed a cylindrical burner 2-1/2" I.D. x 11-1/2" in length.

The center section was formed as a loose coil with spaces between successive turns. These spaces were for the purpose of allowing air to enter the burner. There were indications that additional air was advantageous at this point in the burner. Furthermore, air passing through these spaces would have a cooling effect upon the walls of the burner. The principal cooling, however, was done by water circulating through the coils.

The first tests with the burner were not entirely satisfactory. It was almost impossible to retain the combustion within the burner. This caused very poor operation. The quantity of fuel wused was very limted and the ability to create any pressure within the burner was greatly decreased. Since combustion was occurring outside the exhaust nozzle, there seemed to be one or even two factors contributing to this performance. First, sufficient mixing was not taking place soon enough to allow combustion to proceed to completion within the burner; second, the burner was being cooled so much that the rate of combustion was retarded to the extent that the rate of flow of charge through the burner exceeded the rate of burning of the charge.

A baffle was then placed in the combustion chamber assembly in such a manner that almost all of the air entered the burner through the air cone and very little air reached the cooling coil. In this way, mixing was assured at the entrance to the burner, and also the temperature of the walls of the burner could be controlled by controlling the flow of water through the cooling coil.

Because of the complexity of the burner and the tedious and critical nature of the control of its operation, the burner design was put aside in favor of a simpler design. Since large quantities of air were brought into the combustion chamber for combustion within the burner, a plan was devised for using this air to cool the walls.

In previous chambers deterioration of the walls by the heat within the burner could have been prevented had the heat been readily transmitted through the walls to the surrounding layer of air. To facilitate the transfer of this heat, the air must scour the walls of the burner. Furthermore, more heat could be transferred if the ratio of cooled surface to heated surface was greater than unity. This new burner was designed with these two ideas in mind.

Figure 4 of the Appendix shows the section and detail views of a similar burner. The burner shown in Fig. 4 was a modification of the original design. The basic design was the same in both cases, however. Burner No. 3 was constructed of 34 vertical elements fitted into two end pieces. These elements were made of 1/8" x 1/2" cold roll steel and were fitted into milled slots in the annular shaped end sections. These slots were milled at 45° with the radii of the annular end sections. The assembly formed a burner 2-3/8" I.D. x 11-1/2" in length. The vertical elements were assembled with about 0.003" wide air spaces. These air spaces produced a tangential movement within the burner providing needed turbulence. The vertical elements gave a large ratio of cooled surface to heated surface.

The first tests with the new burner were rather unsatisfactory. The main source of trouble was combustion taking place beyond the exhaust nozzle. Except on rare occasions combustion could not be confined to the burner alone. The reason for this appeared to be that too much air was entering near the top of the burner. Consequently, the optimum mixture conditions were being established at the exhaust nozzle, and the charge was going out the exhaust nozzle before combustion could take place.

In an attempt to remedy this condition rows of holes were drilled around the base of the burner to allow more air to enter at the bottom. Tests showed a definite improvement in the performance of the combustion chamber. However, the operation of the chamber was very unsteady, and control of it was very difficult. More holes were drilled in the base section of the burner to allow even more air to enter near the bottom. This did not improve the performance to a noticeable degree. As a final change in the apparatus, the area of the exhaust nozzle was decreased. This change made a definite improvement in performance. Combustion could be restricted to the burner alone; however, the capacity of the burner to burn fuel was decreased. The tests on this burner indicated that: the velocity through the burner must be slow enough to allow combustion to go to completion within the burner; a highly combustible mixture must be reached at the entrance to the burner; and some of the capacity of the burner to burn fuel must be sacrificed in order to get combustion to occur completely within the burner.

When the burner was inspected after operation, it was found to be in a bad state of repair. The vertical elements were considerably distorted and showed evidence of high temperatures. In this burner design no space had been allowed between the air-fuel cone and the burner. Consequently, the burner could not expand freely under the stimulus of the high temperatures and distorted itself because of this restriction.

The burner was repaired and subjected to further tests. In these tests the burner did not perform satisfactorily. Combustion would not occur within the burner except at infrequent intervals and in general the performance was very erratic. At times when combustion was occurring within the burner the capacity was very low. No appreciable pressure could be built-up within the chamber, so the amount of fuel that could be burned was also low.

It was observed early in the work on combustion chambers that the capacity of a combustion chamber, or the amount of fuel that could be burned within the burner, was dependent upon the pressure within the chamber. This fact was confirmed in each design tried. Until an appreciable pressure of from 15 to 20 psig was obtained in the burner, the amount of fuel that could be burned was small. The explanation of the relationship between capacity and pressure is discussed later in Analysis of Results. Therefore, it is sufficient here merely to mention the fact that the pressure that could be built-up within a burner had a direct effect upon the capacity of the burner.

Since the pressure that could be built-up within the chamber was low and the performance was unreliable, this combustion chamber design was shelved. After the tests the burner was examined and again found to be in a very bad condition. The vertical elements were badly buckled and twisted. They were not burned by the flame. The damage was undoubtedly caused by their inability to expand. It was obvious that the burner design must be altered. With a burner undergoing such distortions it was impossible to maintain constant conditions long enough to form an opinion of the performance characteristics of the chamber. This great distortion explained a great extent the erratic performance of the burner. This burner design was, therefore, shelved, and a new burner was designed incorporating a number of changes suggested by the experience with the previous burner.

The new burner, burner No. 4, was basically the same as the preceding one, the principal difference being the arrangement of the vertical air slots. In this new burner the slots were tapered, i.e., the spaces between the vertical elements were greater at the bottom than at the top. In fact, there were no spaces between the elements at the top. Since, with the previous burner, combustion was taking place outside the exhaust nozzle, it was necessary to introduce the air nearer the bottom of the burner. The vertical elements were, therefore, placed so that most of the air entered the burner at the bottom and progressively smaller amounts entered near the top.

In the previous burner, the effect of expansion of the vertical elements was very destructive to the burner. To allow for the expansion, the burner was suspended within the combustion chamber with a 1/16" space between the air-fuel cone and the burner. Around the top of the burner was a lip which rested on a ring placed in the combustion chamber just below the exhaust nozzle add thus suspended the burner in the chamber. Figures 3 and 4 in the Appendix show this burner in detail.

In preliminary tests with this new burner, combustion still was not confined entirely to the burner. Although there was a definite improvement which indicated that the introduction of air at the bottom was part of the answer to the problem, it was still evident that the most combustible mixture was still being obtained too near the exhaust nozzle for combustion to be completed within the burner. Another factor possibly contributing to combustion occurring outside the burner was too great an ignition lag. This seemed to be a logical reason when the performance of the burner was analyzed. This analysis is discussed in detail in Analysis of Results. At this point it is enough to say that because of the high velocity of the mixture through the burner at high capacity and because of insufficient pressure within the burner, the effect of ignition lag and slow flame propagation were enough to retard combustion so much that combustion could not be completed within the burner. The simple method of overcoming these effects would have been to lengthen the combustion chamber until the time for travel of the mixture through the burner was long enough to allow combustion to be completed within the burner. This however, was not entirely desirable.

It had been observed earlier that when combustion was occurring outside of the chamber, the burner was in effect acting as a mixing chamber. Furthermore, if a secondary combustion chamber were added so that the mixture formed in the first chamber would be discharged into the second chamber where combustion could be completed, the problem of combustion outside the chamber would probably be eliminated.

This arrangement seemed to have many possibilities. Closer analysis, however, indicated that the disadvantages would overcome the advantages. So, the idea of using a secondary combustion chamber, although not abandoned, was definitely put in the background until future developments could justify its use.

The idea of a divided burner, i.e., one with a portion where combustion could be started and a portion where combustion could be completed, seemed to be a feasible and practical answer to the combustion problem, however. Therefore, a precombustion chamber was incorporated into the combustion chamber. This precombustion chamber was formed by two conical sections placed with their bases together. The lower cone contained the fuel nozzle and air holes and was the same air-fuel cone used in previous chambers. Air entered the precombustion chamber through the air holes in the air-fuel cone and formed with the fuel a very rich mixture which was ignited by a spark gap placed in the precombustion chamber. The burning rich mixture was then discharged through an orifice in the top of the precombustion chamber into the burner. Here, more air was introduced through the vertical air slots in the burner and a very combustible mixture was formed and combustion then proceeded in the burner.

In order to assure an adequate supply of air to the precombustion chamber and to maintain a slightly higher pressure than in the burner, separate air supplies to the precombustion chamber and to the burner were installed. It was also felt that separate air supplies would enable more accurate control and study of the combustion chamber performance. The air to the precombustion chamber was called the "primary" air and that to the burner, the "secondary" air.

Burner No. 4 was used in this redesigned combustion chamber. It was again suspended in the combustion chamber with clearance for expansion. Secondary air was brought in on a level just above the orifice between the precombustion chamber and the burner. The performance of this new combustion chamber was very gratifying; it confirmed the belief that complete combustion within the burner could be obtained if suitable provisions for mixing and ignition were provided, namely, the precombustion chamber arrangement. This combustion chamber was put through a number of performance tests. The maximum capacity was the point of greatest interest and the object of the tests was to determine this capacity. Ignition could be accomplished rather well. However, in starting the operation of the combustion chamber, the mixture ratio was very critica Difficulty in starting was encountered unless the mixture was near the correct value. Full capacity of the combustion chamber was reached when all the air that could be supplied was supplied. After about .5 minutes of operation at full capacity, the burner failed and performance ceased. Later inspection showed that the upper portion of the burner had melted and had actually burned. The temperature of the burner had obviously been above 2800^{o} F. Figure 5 is a photograph of burner No. 4 showing the damage resulting from operation at full capacity. Although the performance of the combustion chamber was good, the length of operation was limited by the failure of the burner to withstand the high temperature reached in the combustion process. Since length of operation was an important consideration, design of a new burner was un dertaken in an attempt to overcome the trouble imposed by the high temperatures created in the burners.

In view of the fact that all previous burners had been made of heavy material, i.e., rather massive construction, and had not proved capable of withstanding the great heat within the burner, the possibility of successfully using light gage sheet steel seemed worthy of investigation. In addition to better heat transfer through the walls of the burner (which would lower the temperature of the walls if the conducted heat were removed), greater flexibility in design and easier fabrication of the burner could be achieved by use of light sheet steel. Since the precombustion chamber had proved successful, it was again used in the combustion chamber. Only the burner was redesigned.

There were four burners of the same general design constructed and tested. The basic design was designated as No. 5; the modifications were classified as a, b, c, and d. All of the burners were constructed of 26 gage black iron. The basic design was a burner composed of two sections joined to form a single unit. The lower section was a perforated cylinder into which secondary air entered and mixed with the rich mixture flowing from the precombustion chamber. The upper section of the burner was the actual combustion space. It was slightly conical in shape and extended from the perforated mixing section to the exhaust nozzle. The two sections were joined to form a single unit which was suspended in the combustion chamber in the same manner as burner No. 4. The principal difference in the burners of this general design was in the lengths of the two sections forming the burner. These dimensions were varied in an effort to find the best proportions for the burner.

The construction of the perforated section is rather interesting. It was known that turbulence in the secondary mixing chamber would greatly expedite combustion, and since this was necessary, a method of creating turbulence within the mixing portion of the burner was devised. Circular perforations were used for the entrance of the air. In the perforation process, however, the blanks were not detached from the sheet of metal (which formed the walls), but rather were partially cut out and then folded out from the plane of the metal sheet. In this way the perforation blanks directed the flow of air causing the air to enter the burner tangentially producing turbulence. Figure 6 in the Appendix shows detail views of the perforated section of the burner.

In burner No. 5a, the two sections were joined by screws in three places, leaving a small air gap between the sections. A line of holes was drilled around the top of the burner just under the exhaust nozzle to allow some of the secondary air to flow over the walls of the burner to cool them and then enter the burner just ahead of the exhaust nozzle. Tests on this burner proved it to be very unsatisfactory A "hot spot" developed at the air gap where the two sections of the burner were joined and the burner was badly damaged, Figure 7 in the Appendix is a photograph taken of the burner after it had been in operation at full capacity about five minutes. The failure at the air gap indicated that the mixture for best heat release was being formed at the air gap. The mixture should have been established in the mixing portion so that combustion could have taken place throughout the burner rather than at one place in the burner.

Burner No. 5b had a shorter mixing section than No. 5a. In addition, the two sections were welded together so that there was no air gap. This burner also had a line of air holes around the top so that air could flow over the outside of the walls and cool them. The tests on this burner were very informative although the performance of the burner was far from satisfactory. After about five minutes of full capacity operation, the combustion chamber ceased to operate properly, i.e., the operation could no longer be controlled. Later inspection showed that the burner had been burned away in the region of the air holes at the top. As in the previous burner, it was evident that proper mixing was not being obtained in the mixing portion of the chamber. In both cases, air entering in the combustion region of the burner had created a mixture releasing enormous quantities of heat in a small volume. It was obvious that until proper mixing was achieved in the lower part of the burner any air opening in the upper portion of the burner would produce a "hot spot". Figure 8,,is a photograph of burner No. 5b, taken after its failure.

Burner No. 5c was designed with the hope of overcoming the difficulties previously encountered. Since as long a space as possible was needed for combustion, the mixing portion of the burner was shortened still more. Because it was shortened, more air holes were added in order to admit the same amount of air. No holes were drilled around the top of this chamber to allow air to flow over the burner, because of previous experience with the air holes. The results obtained with this burner were about what were expected. After about three minutes of operation at full capacity, the burner failed. An examination of the burner showed that it had been severely damaged. The upper portion where combustion occurred had melted and burned almost beyond recognition indicating excessive temperatures over quite a region in the burner. It was obvious that lack of air circulation over the surface of the burner had promoted the destruction of the burner. This was definite proof that air circulating over the walls of the burner could be beneficial in cooling the walls. Figure 9 in the Appendix is a photograph of the burner showing the deterioration affected during operation. Since none of these three burners had proved entirely successful, a major design change was felt to be necessary.

The basic principal of the three previous burners was believed to be worth retaining, however. These burners had shown beyond any doubt that combustion could be completed within the burner if proper mixing of the charge were achieved near the entrance to the burner. Furthermore, the precombustion chamber and the mixing portion of the burner had functioned well in each of the three cases. The simplicity of design and ease of fabrication of the burners used before made the further use of the basic design attractive.

Burner No. 5d was very similar to the other three burners of this series. The perforated section was 6 inches in length and the combustion portion was 6 1/2 inches long. No holes were drilled around the top for cooling. The combustion chamber design was changed considerably. In previous chambers the secondary air was brought into the air space around the burner at the bottom of the burner. It had been brought in in an axial direction. This was changed so that it could come in at this position in the chamber but in a tangential direction. In addition, arrangements were made so that part or all of the secondary air could be brought in at the top of the combustion chamber. Control valves were provided so that the amount of air brought in at each position could be controlled. The air entered in a tangential direction. By bringing the air in at the top of the combustion chamber, the air passed over the burner walls on its way to the mixing chamber thus cooling them. Figure 6 shows a cross section view of the entire combustion chamber assembly as well as detail views of the burner and the air inlets.

A number of tests were performed on this burner and all of them were very encouraging. The burner was operated at full capacity on a number of occasions for periods of time ranging from five minutes to fifteen minutes. The burner showed evidence of high temperatures encountered, but it was not damaged to the point of uselessness. Altogether the burner was operated for about 45 minutes. Figure 10 is a photograph of the burner taken after its operation. Combustion occurred within the chamber and high heat release rates were obtained. All of the secondary air was delivered at the top of the combustion chamber in order to get the maximum cooling effect on the burner. Reasonable fuel-air ratios were maintained during operation. The performance of this burner is explained in detail by the results given in Table I and by the discussion in Analysis of Results.

VI. ANALYSIS OF RESULTS

It was pointed out in the Introduction that the design of a combustion chamber entails a consideration of the desired performance characteristics, an analysis of the factors affecting these performance characteristics, and a coordination of these factors in such a manner as to produce the desired performance characteristics. When the investigation was first started, few of the factors affecting performance were known. However, as the investigation proceeded, more became known, and measures were taken to satisfy the restrictions imposed by them.

The designing of a combustion chamber seems relatively simple at first thought. The requirements are simply a chamber in which combustion can occur, a supply of fuel and a supply of air. When the investigation was first started and little was known about the problems connected with high heat-release rates, the combustion chambers were indeed simple affairs. In an earlier report on the subject, Progress Report on Theoretical and Experimental Investigation of Jet Propulsion Devices, a detailed account was given of the steps involved and difficulties encountered in the design of a practical chamber. In the early work, the principal goal was to work out a basic design for a combustion chamber, a design which could be used for study so that the problems of combustion and combustion chamber performance could be analyzed and improved. The work was successful in that a basic design was worked out.

This later investigation concerned the study of the combustion process, control of the variable factors affecting combustion, and the refinement of the basic design. In the preliminary work on the problem when the basic design was being worked out, a number of problems were encountered which were both baffling and troublesome. The two causing greatestdifficulty were the deterioration of the burner by the intense heat of the combustion process and the tendency for combustion to occur outside the burner, i.e, beyond the thrust nozzle. The answer to the first of these two problems seems to be either to find and use a heat resisting material or to cool the burner so effectively that it will not be affected by the heat. The answer to the second problem is much more complex. When the investigation was first started, little could be done to improve combustion until information pertaining to it were gathered and analyzed. Then some very important facts became known and their influence on the overall picture became evident. There were other considerations, of course, in the design of a good combustion chamber. They were, however, secondary to the other two problems mentioned above. In this secondary classification were considerations of size and proportions of the chamber, capacity of the burner for releasing heat, consistency of performance, and starting ability. These were considered of secondary importance, because, although they were important in the final evaluation of a combustion chamber, they were not suitable criteria for rating basic designs. It was felt that once a suitable basic des'gn were found, it could be modified to meet other requirements that were desirable.

All of the burners designed and tested were designed with the idea of the burner withstanding the heat of combustion foremost in mind. The experience with the porcelain-section burner indicated that the task of finding heat resistant materials was lengthy and probably fruitless. Incuiries were made of companies manufacturing alloy metals and none could suggest a material suitable for the work. The fragile nature of porcelain made its use unattractive. Therefore, cooling the walls of the burners was the only alternative.

The water cooled burner was not a complete success. Nevertheless, it would seem to offer possibilities. Control of the temperature of the burner wall would be possible. It was noted during experiments with this burner that wall temperatures had a great effect upon the combustion within the burner. Thus, a certain amount of control over combustion could be had by controlling burner wall temperatures. If water were used as a coolant, in the short lived application of the burner this water could be converted to steam in the cooling element and this steam then injected into the burner just below the thrust nozzle to increase the mass of gas expanding through the nozzle. This increase in mass would increase the thrust of the nozzle. This idea seems to be plausible in connection with an application of the burner to the "flying-bomb".

For burners to be used in aeroplanes the complexity of a cooling system containing heat exchangers and perhaps storage tanks and pumps would be undesirable. In this case the obvious medium for cooling is air. Furthermore, the use of the air for combustion is logical. This air would be under pressure and could be directed so as to flow over the heated surfaces before entering the burner.

The last combustion chamber built and tested incorporated this idea. The five preceding combustion chambers were also designed with the idea of cooling the burner by the combustion air; these designs, however, were rather crude and ineffectual. Combustion chamber No. 5d was successful and proved that the life of the burner could be prolonged by cooling it with the combustion air. Undoubtedly, future work on combustion chamber designs will produce refinements allowing more effective air cooling of the burner.

The complete answers to the problems of combustion were not obtained in this investigation. Many important facts concerning the problems were learned, however. The problem of restricting combustion to the burner was the most serious difficulty encountered. The importance of this problem should be recognized at once. Unless combustion is restricted to the burner, the purpose of the combustion chamber is lost. By restricting combustion to the burner, control over combustion and utilization of the combustion gases are possible. When combustion occurs beyond the thrust nozzle, the fuel-air ratio has no significance and the rate of heat release is meaningless.

A number of conditions were found to affect combustion; these were velocity of charge through the burner, pressure in the burner, completeness of mixing of fuel and air, and ignition lag. It is easily understood how the velocity of the charge or mixture through the burner directly affects the combustion process. If the velocity is too high, the time available for combustion within the burner is less than the time needed for complete combustion. If the velocity is too low, the greatest capacity of the combustion chamber can not be realized. The ideal velocity would be such that the time for the mixture to travel through the burner and the time for the mixture to burn completely would be the same. Some method of controlling velocities through the burner would be necessary, because the time for combustion would vary with the fuel-air ratio of the mixture, pressure in the burner, and temperature in the burner. Although the relationship between velocity of the charge and the combustion process is known and has been investigated, the task of coordinating the two was beyond this stage in the investigation.

The question of capacity of the burner is of particular interest and importance. Obviously, it is desirable to burn as much fuel as possible within the burner, for the greater the quantity of fuel burned the greater the quantity of exhaust gases produced. However, all the fuel must burn within the burner or the advantage of greater fuel consumption is lost. If combustion occurs beyond the exhaust nozzle, then the additional fuel burned above that which could be burned entirely within the burner does not represent an increase in capacity, but rather it causes a decrease in thermal efficiency of the combustion chamber, since the additional fuel does not produce exhaust gases which can be utilized by the exhaust nozzle.

Furthermore, the quantity of fuel that can be mixed with air, ignited easily, and burned in the combustion chamber, can not be taken as a measure of the effectiveness of a combustion chamber design. The only correct method of rating a burner is by the amount of fuel burned (or heat released) entirely within the burner, for only after the fuel is burned can the hot, expanding exhaust gases be used.

The fuel-air ratio of the mixture is a factor in the combustion process. The fuel-air ratio affects the rate of flame propagation and also the ability of combustion to be completed within the burner. If the mixture is too lean, ignition lag becomes excessive and the rate of flame travel is reduced. On the other hand if the mixture is too rich, combustion cannot be completed within the burner. The chemically correct fuel-air ratio is about 0.0665. When mixtures much richer than this are used, it is inevitable that some combustion will occur outside the burner where air is available. It is desirable, however, to have a rich mixture at the point of ignition. Then sufficient air should be introduced into the burner to produce as nearly as possible the chemically correct mixture.

It was mentioned in Combustion Chamber Studies that some difficulty was encountered with ignition. This difficulty was in securing an ignitable mixture in the fuel-air cone where the ignition spark was located. The time available for igniting the mixture was very short, so the mixture had to be very receptive to the spark if ignition was to occur. This appeared to be merely a question of producing the right fuel-air ratio, but so much trouble was experienced that some positive method of securing ignition was demanded. The idea of a precombustion chamber was the answer. The original patent claims for the precombustion chamber as applied to the compression ignition engine speak of the precombustion chamber as a method of ignition. A rich mixture is ignited in the precombustion chamber and discharged into the main chamber where combustion takes place. The precombustion chamber idea was incorporated in the combustion chamber design and proved successful. There is some doubt as to why the precombustion chamber improves ignition. The probable answer is that by spraying the fuel into a small closed space a highly ignitable mixture is formed; then by discharging this burning mixture through an orifice into moving air in the burner excellent mixing of the rich mixture with the air is achieved and combustion is completed rapidly within the burner.

It is important that all of the secondary air (air for combustion in the burner) enter the burner near the orifice from the precombustion chamber. Otherwise, combustion will be delayed, perhaps even prevented from being completed in the burner.

It was found that the capacity of the burner or the amount of fuel that could be burned was a function of the pressure in the burner. After the warming up period, the pressure in the burner had to be increased before an appreciable quantity of fuel could be burned. This made the size of the exhaust nozzle critical, because the size of exhaust nozzle determined how much pressure could be built up in the burner. The reasons for the effect of pressure upon combustion are not fully known. It seems probable, however, that pressure in the burner is an index to the weight of air in the burner. The weight of fuel that can be burned is, of course, dependent upon the weight of air available.

The higher the pressure in the burner the greater the weight of air and the greater the weight of fuel that can be burned. There is a limit to the pressure that can be used, however, since t air for combustion must be compressed. This limiting pressure is that pressure which to obtain will require more work from the compressor than can be realized from the additional fuel burned because of the increase in pressure.

It also seems probable that combustion is improved by higher pressures in the burner because the rate of flame travel increases with pressure. This is because the mixture is more dense and better mixing has taken place by discharging from the precombustion chamber into the more dense air in the burner.

The final combustion chamber designed and tested was designed with the facts discussed i his section in mind. The performance of this combustion chamber was g fying because it substantiated most of the theories proposed regar ing the design and performance of a high heat-release combustion chamber. By co ling the burner walls with the combustion air the life of the bu ner was lengthened; the precombustion chamber provided effective starting as well as good ignition of the charge; the combustion chamber was operated at rear nable fuel-air ratios; combustion could be restricted to the burner; and all of these were accomplished without using special materials, high pressures, or decreasing the heat-release rate.

As shown in Table I, the final test or this chamber gave a heat-release of 21,600,000 B/hr per ft^3 of standard atmospheric air in the burner. The chamber operated at a fuel-air ratio of 0.0789; although it is on rich side, very little combustion occurred outside the exhaust nozzle. Since the fuel-air ratio was on the rich side, the heat release of 21,600,000 B/hr ft^3 is slightly high because some of the combustion had to take place in the outside atmosphere. Given also in Table I are the heat releases assuming a chemically correct fuel-air ratio and all the air used for combustion. These heat releases are more nearly correct.

This combustion chamber design is capable of refinement and improvement. Stainless steels would be much better for burners and mixing chambers. Better distribution of air to the burner would improve mixing and combustion. An augmentor type of device was used on chamber No. 5d as shown in Fig. 6 to cool the exhaust nozzle. A great deal of work remains to be done on this part of the apparatus. Optimum size and shape of the nozzle should be determined and here too stainless steel could be used to advantage. The problem of fuels for such a combustion chamber has not been investigated. Thorough tests of various grades of fuel oil, kerosene, and gasoline should be made. The question of optimum pressures in both the precombustion chamber and the burner is at present unanswered. All of these can be answered only by future investigation.

VII. CONCLUSIONS

The burners that were constructed and tested in this study have shown capacities for burning large quantities of fuel per unit of combustion-chamber volume, but the temperatures attained by the metal walls, when operating at high rates, were excessive. Attempts to cool the burner walls by air circulation or otherwise were successful in prolonging the life of the burners. However, complete immunity to the high temperatures was achieved only by cooling to the point where combustion was unsatisfactory. It became evident that non-volatile fuels require extremely high burner-wall temperatures if vaporization, ignition, and mixing with air are to be effected in the short time allowable in a burner of this type.

The precombustion chamber type burner used in the most recent tests appears to offer a solution to at least a portion of the problem by speeding up the charge preparation processes. Initial mixing, partial vaporization, and ignition of the rich mixture formed in the precombustion chamber, and its subsequent discharge at increased velocity into the main chamber result in more rapid combustion. Secondary air introduced with axial swirl around this jet of burning fuel carries combustion to completion in a shorter space than when the liquid is sprayed directly into the burner proper.

So many variables are involved in this two-compartment burner that considerable experimentation is necessary to establish optimum operating conditions. The weight ratio of primary to secondary air, size of connecting orifice, ratio of chamber volumes and size of outlet nozzle all affect performance and must be coordinated to produce best results. It is possible that the perforated inner sleeve can be modified to the extent of reducing it to a short baffle at the secondary air inlet.

It appears likely that this construction can be applied to a jet engine advantageously by forming a single annular combustion chamber continuously surrounding the compressor. The annular chamber formed by two concentric cylindrical walls would provide considerably more combustion-chamber volume in the same overall space than the total of the separate cylindrical chambers now used because it would include the interstices now wasted. The secondary air, if introduced with a circumferential component of velocity, would produce a spirally rotating flame that should readily mix the air with the unburned fuel and bring combustion to completion within the burner.

An appropriate number of precombustion chambers, arranged around the front end of the annular chamber, would introduce the mixture of fuel and primary air into the secondary air in the main chamber well prepared for burning. The increased combustion-chamber volume and decreased wall area should improve combustion, while the simplified construction in the hottest region should prove longer lived than the separate burner arrangement

The advantages offered by an annular burner of this sort, if the details can be worked out, are obvious. The possibility of perfecting the design appears to be great enough to justify further experimentation.

VIII. APPENDIX

(a) Table I

(b) Computations

(c) Photographs, Drawings

TABLE I

Performance data and results from two tests on Combustion Chamber No. 5, Burner No. 5d.

Test No.	Pressure, psia Fuel	Pressure, psia Primary Air	Pressure, psia Secondary Air	Fuel lbs/hr	Primary air, lbs/hr	Secondary Air, lbs/hr	Total Air lbs/air	F/A	Heat Release B/hr ft^3 *
1	354.5	33.5	29.5	54	145	238	383	0.141	22,400,000
2	354.5	30.5	26	52	155	497	638	0.0798	21,600,000

These heat releases do not represent true conditions. Since the fuel-air ratios are on the rich side combustion was not completed within the burner. Assuming the chemically correct fuel-air ratio of 0.0665 as the limit for combustion within the burner, the true heat releases within the burner are:

Test No.	Pressure, psia Fuel	Pressure, psia Primary Air	Pressure, psia Secondary Air	Fuel lbs/hr	Primary air, lbs/hr	Secondary Air, lbs/hr	Total Air lbs/air	F/A	Heat Release B/hr ft^3 *
1	-	-	-	25.5	-	-	383	0.0665	10,550,000
2	-	-	-	42.5	-	-	638	0.0665	17,600,000

* Heat release in terms of B/hr per ft^3 of standard air in the burner. Standard conditions are 60 °F and 29.92 in Hg.

Sample Comutations

Precombustion chamber volume . . . . 0.0046 ft^3

Burner volume . . . . 0.0355 ft^3

Correcting these volumes of air to volumes at standard conditions ($60^{o}F$ and 29.92 in.Hg).

Precombustion chamber

$$V_c = 0.0046 \times \frac{-62.2 \text{ in.Hg}}{29.92 \text{ in.Hg}} \times \frac{60 \text{ F}}{60 \text{ F}}$$

$$V_c = 0.00956 \text{ ft}^3$$

Burner

$$V_c = 0.0355 \times \frac{53.0 \text{ in. Hg}}{29.92 \text{ in.Hg.}} \times \frac{60 \text{ F}}{100 \text{ F}}$$

$$V_c = 0.0378 \text{ ft}^3$$

Total corrected volume = 0.0473 ft^3

Using Bureau of Standard approximation for heating value of fuel -

$$H.V. = 18{,}690 + (API - 10)36$$

$$H.V. = 18690 + (37 - 10)36$$

$$H.V. = 18690 + 972 = 19{,}662$$

Use H.V. as 19,600 B/lb.

Test 1

Heat release = 19,600 x 54 = 1,060,000 B/hr

Heat release per ft^3 of standard air in burner.

$$\frac{1{,}060{,}000}{0.0473 \text{ ft}^3} = 22{,}400{,}000 \text{ B/hr ft}^3$$

Test 2

Heat release = 19,600 B/lb x 52 lb/hr

Heat release = 1,019,000 B/hr

Heat release per ft^3 pf combustion chamber volume

$$\text{Heat release} = \frac{1,019,000}{0.0473\ ft^3}\ B/hr = 21,600,000\ B/hr\ ft^3$$

Assuming F/A of 0.0665 and that all of the air in the burner is utilized for combustion:

Test 1

Wt. of air = 383 lbs/hr

Wt. of fuel = 383 x 0.0665 = 25.5 lbs.

Heat release = 19,600 x 25.5 = 499,000 B/hr

Heat release per ft^3 of standard air in the burner

$$\frac{499,000\ B/hr}{0.0473\ ft^3} = 10,550,000\ B/hr\ ft^3$$

Test 2

Wt. of air = 683 lbs/hr

Wt of fuel = 683 x 0.0665 = 42.5

Heat release = 19,600 x 42.5 = 833,000 B/hr.

Heat release per ft^3 of standard air in the burner.

$$\frac{833,000\ B/hr}{0.0473\ ft^3} = 17,600,000\ B/hr\ ft^3$$

Fig. 1: Burner No. 1 showing procelain center section and perforated mixing section.

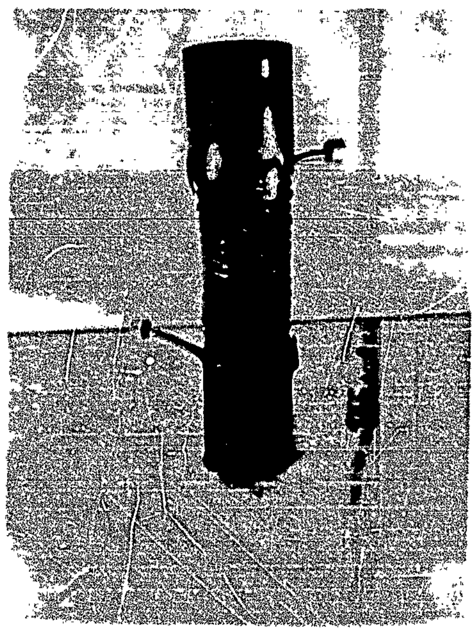


Fig. 2: Burner No. 2 showing the water cooled section mounted between the mixing section and the upper burner section.

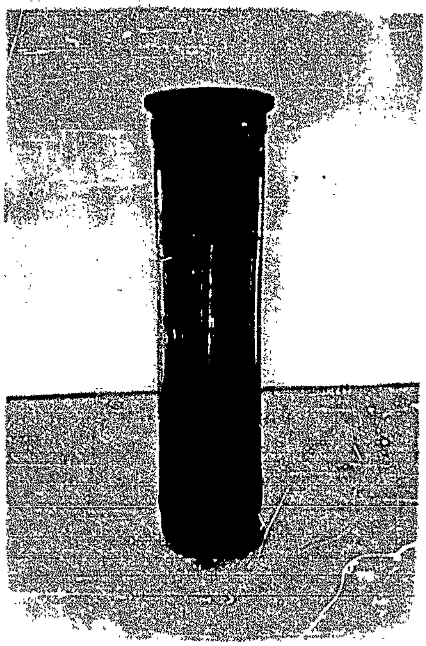
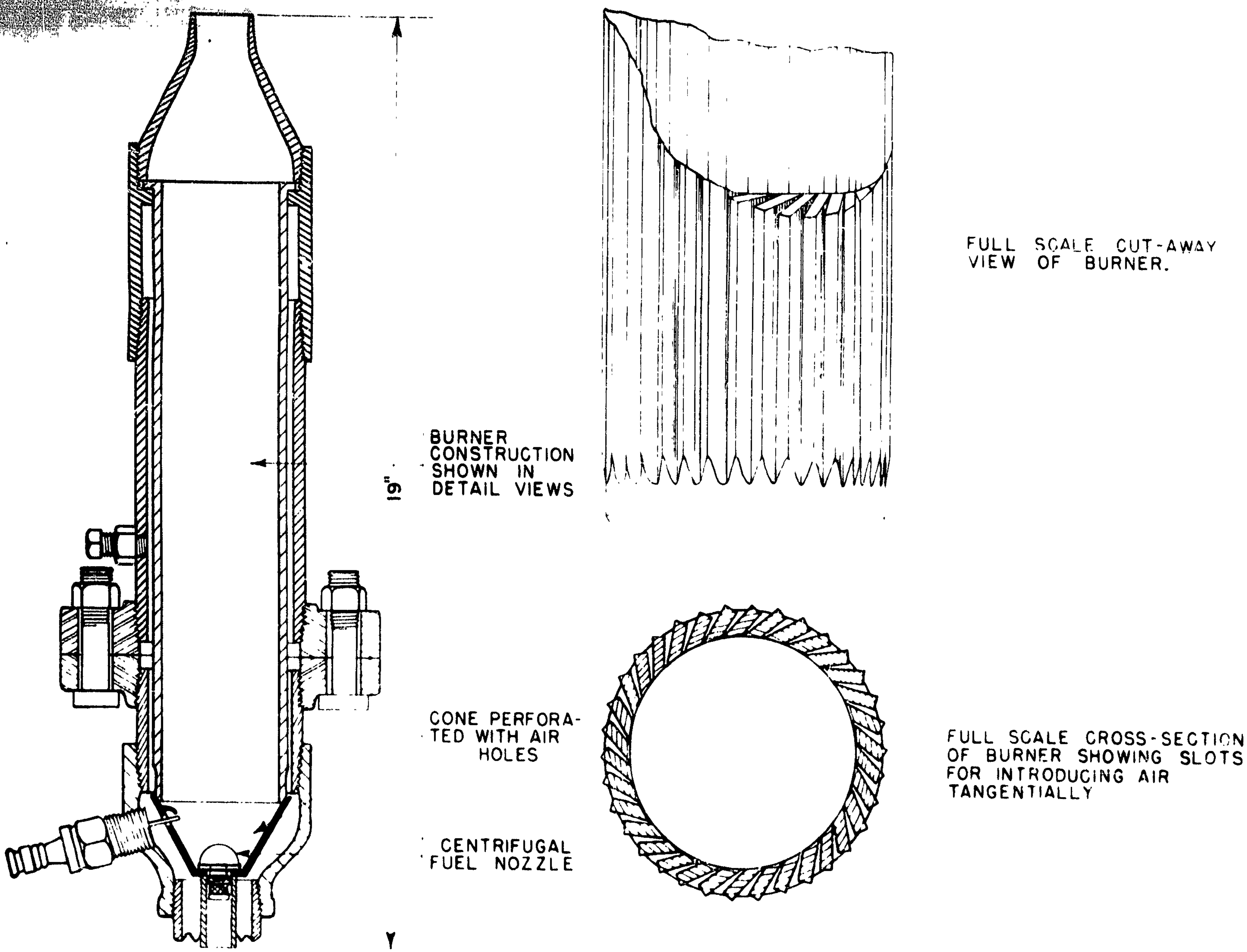


Fig. 3: View of burner No. 4 before being tested showing the design of the burner.

Fig. 5: View of burner No. 4 after being tested. This shows the damage inflicted on the burner by the high temperatures in the burner.



SECTION VIEW OF COMBUSTION CHAMBER ASSEMBLY

SCALE ½" = 1"

DETAIL VIEWS OF BURNER

FIG 4 SECTION AND DETAIL VIEWS OF COMBUSTION CHAMBER NO. 3

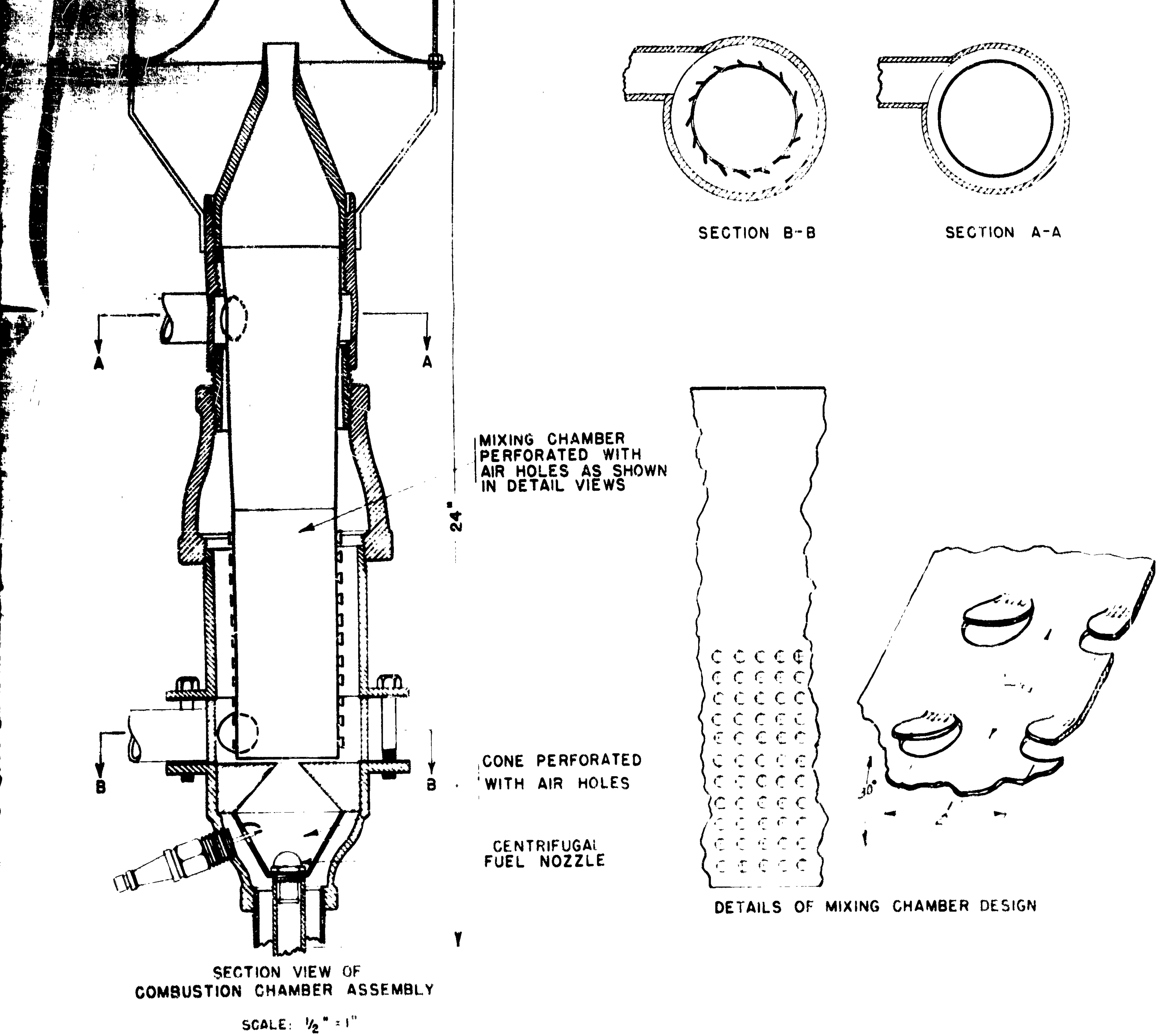


FIG. 6: SECTION AND DETAIL VIEWS OF COMBUSTION CHAMBER NO. 5

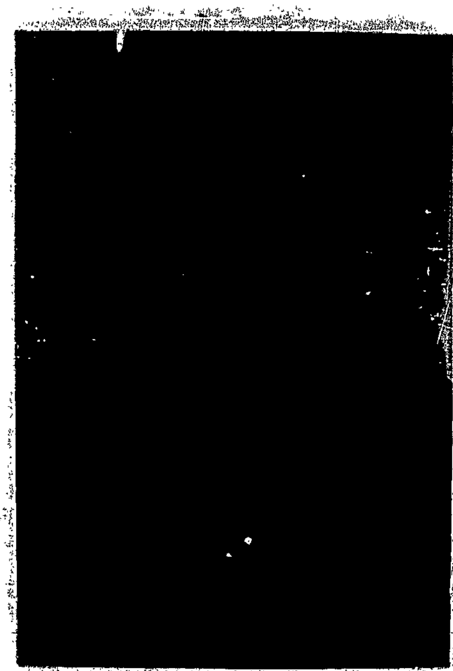


Fig. 7: Burner No. 5a after about 5 minutes operation at full capacity. View shows burner design as well as damage to the burner.

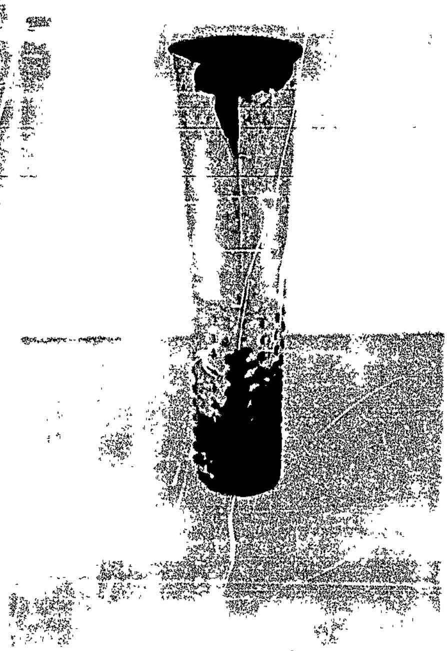


Fig. 6: View of burner No. 5b showing burner design and details of its failure.

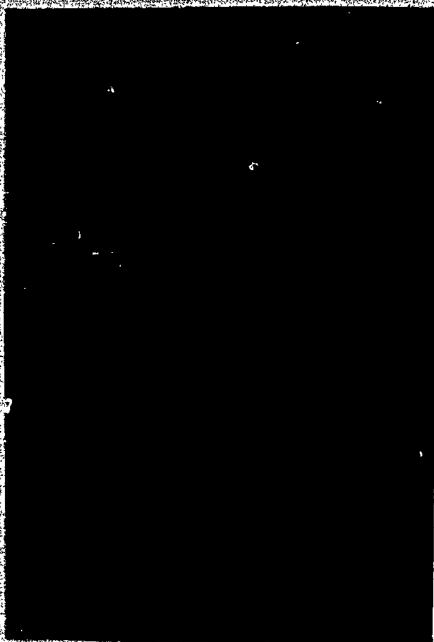


Fig. 9: Burner No. 5c showing the destruction caused by the high temperatures reached in the combustion chamber.

Fig. 10: Burner No. 5d. In this view the burner is in an inverted position. This view was taken after the burner had been operated about 45 minutes without failure.

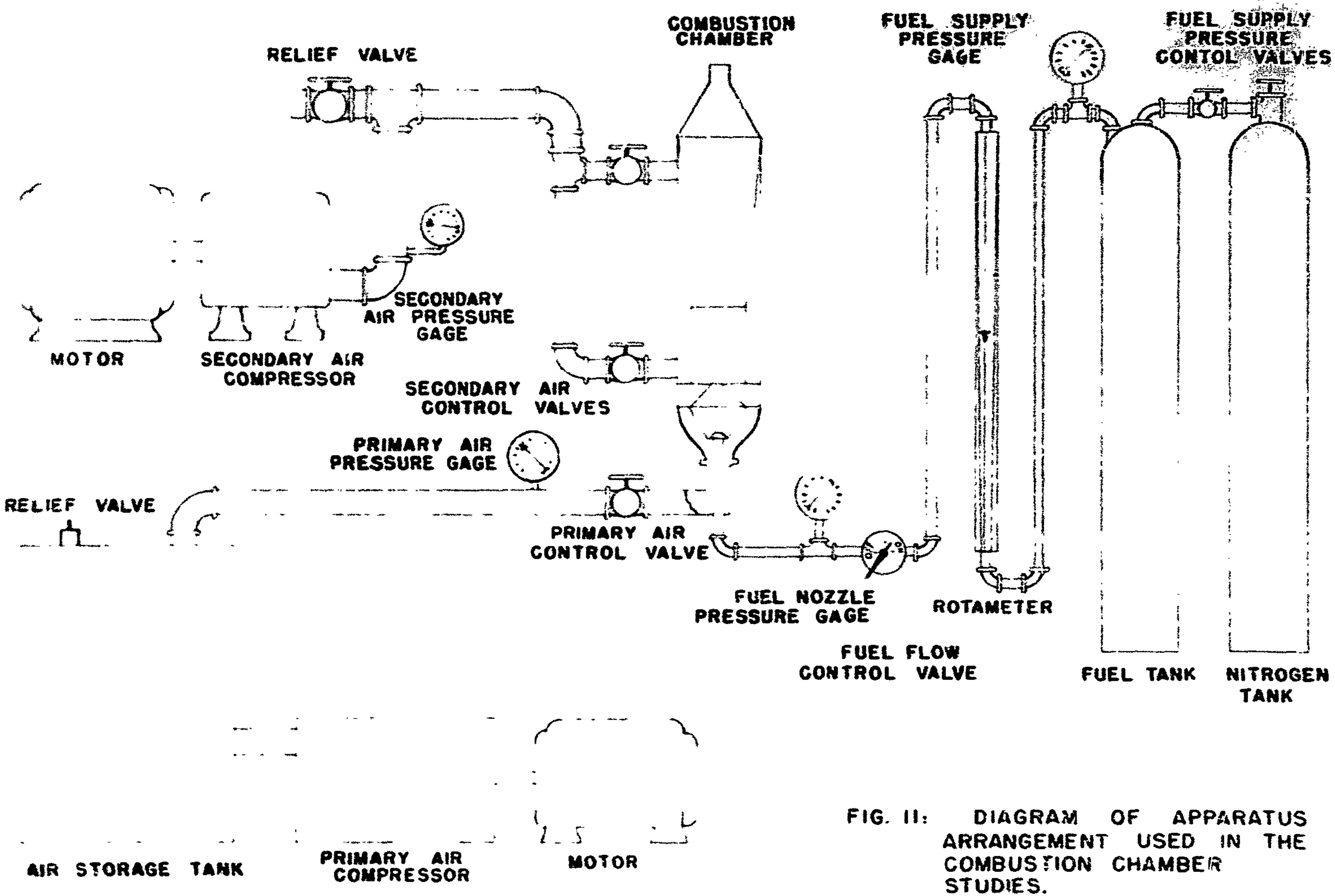


FIG. 11: DIAGRAM OF APPARATUS ARRANGEMENT USED IN THE COMBUSTION CHAMBER STUDIES.

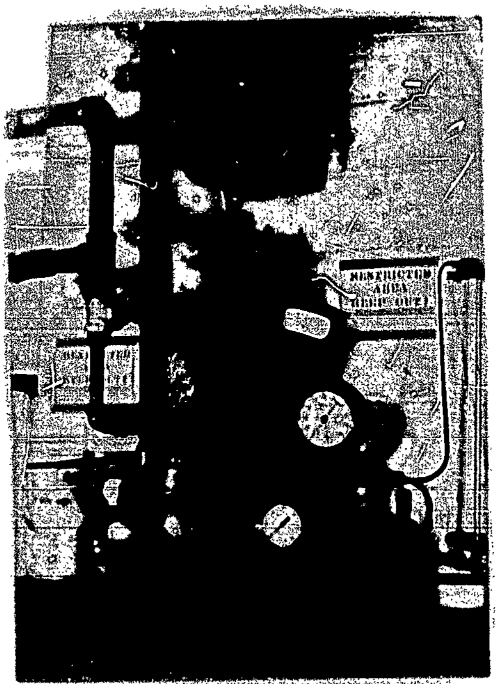


Fig. 12: View of the experimental apparatus showing combustion chamber No. 5 in position for test.

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Experimental Investigation of High Heat-Release Combustion Chambers

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